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MODELING WATER LOSSES FOR MOVING SPRINKLER SYSTEMS

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SUMMARY:

Field water balance measurements using monolithic lysimeters were used to make comparisons and validate the Cupid-DPE model for predicting water loss partitioning during sprinkler irrigation from a moving lateral system. Comparisons indicate good agreement between measured and modeled transpiration, soil evaporation, and total ET rates during the day of irrigation. Soil evaporation rates were under-predicted for the day following irrigation. Droplet evaporation represented less than 1% of the total water loss for the day.

KEYWORDS: evapotranspiration, transpiration, lysimeter, sprinkler

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INTRODUCTION

Water distribution and application efficiency are important parameters to consider when evaluating the performance of an irrigation system. Water that is applied to crops is most effective when it enters directly into the transpiration stream and contributes to dry matter accumulation. However, water applied by overhead sprinkler systems is subject to environmental effects, including direct evaporation of droplets before they reach the canopy, and evaporation from the wetted leaves and soil. The amount of evaporation from the soil and wetted canopy is influenced by energy exchanges associated with the cool water and the amount of leaf area. Transpiration occurs even without irrigation, but the total amount will decrease as evaporation of water from the wetted canopy increases (Norman and Campbell, 1983), although the two will not be at the same rate. Because of these numerous interactions, predicting the true losses from an irrigated crop requires a careful analysis which is best accomplished by considering the energy balance of the plant environment with a droplet evaporation model.

Thompson et al. (1993) have presented a combined droplet evaporation-trajectory and plant-energy balance model, Cupid-DPEVAP. This model was validated for a solid-set irrigation system with impact sprinklers watering a corn canopy. The model was used to quantify the partitioning of water losses among droplet evaporation, evaporation from the wetted canopy and soil, and transpiration during irrigation.

The objective of this study was to validate the Cupid-DPE model during overhead irrigation of a crop canopy when using a moving lateral system. Field measurements included soil evaporation, transpiration, total crop evapotranspiration (ET), irrigation applications, plant growth, soil water content, and required climatic parameters.

PROCEDURE

Instrumentation:

Field measurements were conducted at the USDA-ARS research laboratory located near Bushland, TX (35.2 deg. N. lat.; 102.1 deg. W. long.; 1,170 m elev.). Two weighing lysimeters (Marek et al., 1988) containing monoliths of Pullman clay loam soil (Schneider et al., 1988), 3 m by 3 m with a depth of 2.3 m, and centered in a 5-ha field, were used in collecting data. Measurements included crop transpiration, evaporation from the soil and canopy, and net irrigation applications. Micrometerological measurements were recorded within each lysimeter, along with measurements of air and dew point temperature, humidity, solar radiation, and wind speed at an elevation of 2 m. Additional measurements of windspeed and air temperature were measured at 10 m elevation. The lysimeter and field energy balance instrumentation was sampled at 1 hz and averaged for 5 min. The 5-min. means were then composited into 30-min. means.

Transpiration was measured in three to five plants in each lysimeter by the heat balance method using Dynamax Inc. sap flux gauges. Measurements were recorded during 15 min. intervals for selected days of irrigation. Total transpiration was estimated by multiplying the mean measured plant transpiration by the mean lysimeter plant density (approximately 6 plants m^{-2}). A Pioneer corn variety (3124) was planted with row spacings of 0.75 m.

Soil evaporation was measured using two types of small lysimeters based on the techniques described by Klocke, et al. (1990). The volume of the micro- and mini-lysimeters were 442 cm^{-3} and 472 cm^{-3}, respectively.

The lysimeter field was irrigated with a 450 m long electrically powered, lateral-move sprinkler system capable of irrigating the two lysimeters simultaneously. At 100% timer setting, the control tower speed was about 2 m min^{-1}. The system was equipped to use impact sprinklers, spray nozzles, and LEPA devices (not reported here). Impact sprinklers were placed atop the 168 mm OD pipeline, 6.1 m apart and 3.5 m above the ground. Spray nozzles were placed 3.2 m apart on drop tubes 1.5 m above the ground. Average discharge rates were approximately 6.0 and 6.4 L min^{-1}, respectively for the impacts and sprays. Water pressure was approximately 234 and 220 kPa, and nozzle sizes were 6.7 and 3.2 mm, respectively for the impact sprinklers and spray nozzles. Three 200 mm diameter tipping bucket rain gauges (0.25 mm tip^{-1}) were used to measure irrigation applications.

A more complete description of the field instrumentation and procedures can be found in Martin, 1991.

Modeling Procedures:

Two irrigation events were selected for simulation to compare with measured water losses for each sprinkler type. These were days 186 and 192. A summary of the measured weather input values are listed in Tables 1 and 2, respectively. Irrigation water temperature for day 186 was 17.8 degrees C, and 22.1 degrees C for day 192. (Water was supplied from a reservoir filled from ground water wells, therefore water temperature varied depending on when the reservoir was refilled.) Each simulation consisted of five total days; three prior to the irrigation to establish the required environmental profiles, the day of irrigation, and the day following irrigation.

The upper boundary layer was assumed to be unaffected by irrigation, and was fixed at a height of 6 m above the ground. Although the model is one dimensional, advection can be approximated by varying the height of this boundary. The closer the boundary is placed to the sprinkler and canopy, the greater the assumed effect of advection. The prevailing hot, dry, windy conditions around Bushland lend themselves to greater effects due to advection. The maximum droplet trajectory was 0.2 m (impact) above the sprinkler, leaving 2.3 m between this maximum height and the upper boundary. For situations where the advective conditions are less pronounced, this upper boundary can be raised. During irrigation, the environment below this boundary is influenced by the evaporation and transpiration through the energy balance. This feedback mechanism permits the prediction of a realistic environment so that previous water losses affect future water losses.

In order to improve computational speed of the DPEVAP model, an empirical regression model (DPE) was developed based on output from the DPEVAP model as a function of irrigation water temperature, droplet size, wind speed, air temperature, and vapor pressure. This permitted the use of 40 droplet sizes to represent the volume frequency distribution for each sprinkler type. The regression model fit the DPEVAP predictions very closely, with r^2 values of greater than 0.98 for all energy balance terms.

RESULTS AND DISCUSSION

A summary of field conditions during days 186 and 192 are listed in Table 3. Figure 1 shows the application rate pattern for the impact sprinkler and spray nozzle for an application depth of approximately 25 mm. Note that the impact sprinkler applies water over a given point for about 115 minutes, while the spray nozzle duration is about 45 minutes. Peak application rates are approximately 18 mm h^{-1} and 68 mm h^{-1} for the impact and spray, respectively. Under similar environmental conditions, one would expect the longer irrigation duration of the impact sprinkler to result in greater canopy evaporation for the same application depth. Soil evaporation might also be greater for the impact due to the fact that the wetted diameter is larger, therefore a given area would be wetted sooner than with the spray, although this difference may be minor.

Comparisons between transpiration amounts predicted by the model and stem flow measurements for irrigated days of 186 and 192 are shown in Figures 2, 3, and 4. Irrigation began at 12:05 on day 186 with the spray nozzle (southeast lysimeter, SE-ly), and lasted for 45 minutes. Values shown are 15 minute averages. Note that the predicted and measured values are very similar, with the model responding slightly later than the measured values, both at the beginning and the end of the irrigation. The sap flow readings also indicated a lower measured transpiration rate during the mid portion of irrigation than the model predicted. On average, transpiration rates were lowered 70 to 80% during irrigation.

Results shown in Figures 3 and 4 are for day 192 for the spray (northeast lysimeter, NE-ly) and impact sprinkler (SE-ly), respectively. For this irrigation, transpiration rates were under-predicted for the spray irrigation and over-predicted for the impact. The poorer fit on day 192 compared to day 186 may be due in part to the windier conditions. For example, wind velocities (at 6 m elevation) were in excess of 7 m s^{-1} during much of the irrigation for day 192, but about 4.5 m s^{-1} on day 186. It should also be noted that the measurements represent three to five plants within each lysimeter, which had a surface area of 9 m^{-2} and plant population of 6 plants m^{-2}.

The comparison of measured soil evaporation rates with values predicted by the model are shown in Figure 5. The time period covered is from just after the end of irrigation on day 192 through day 193. Measurements are shown for both the furrow and wheel track of the lateral. The predicted values are for the spray application (impact values were similar), and match closely with the measured values immediately after irrigation and on through the night. However, the rate is underpredicted during the following day, which may be due in part to the procedure used in the model to estimate vertical water movement to the soil surface as evaporation continues.

The summation of individual parameters representing evapotranspiration (ET) for day 192 for the spray and impact irrigated lysimeters are shown in Figures 6 and 7, respectively.
The predicted ET for the spray application matches closely with the measured value during the morning. During the irrigation (12:35 to 13:20), the model indicates an increase in ET rates as the canopy and soil are wetted. It is difficult to determine an exact measurement of ET from the lysimeter during irrigation because of the simultaneous addition of water; therefore direct

measurements during this time are not shown. After irrigation, the model slightly under-predicts ET but the trends are very similar. For the impact case, the model predicts slightly higher ET losses than measured during the morning, and only slightly lower during the afternoon following irrigation.

Following the independent validation/comparison based on soil evaporation, transpiration, and total ET rate, the model was used to predict the partitioning of water losses for both the spray and impact sprinklers, including droplet evaporation losses. Figures 8 and 9 show these rates for the spray and impact case, respectively, for day 192. Figure 10 is included to show what the predicted losses would have been had there been no irrigation on that day. As expected, all three figures indicate the same rate of water usage prior to irrigation. Transpiration is the dominant water use until the canopy is wetted, and then canopy evaporation becomes the major water loss component, with transpiration about 25% of its former rate. Because the irrigation duration with the impact is longer, the loss due to canopy evaporation continues longer than for the spray irrigated area. In each case, recovery of transpiration begins within one hour after irrigation ends. The decrease and subsequent increase in transpiration rate at about 15:00, as shown in Figure 10, is due to a reduction in solar radiation due to cloud cover.

Figure 11 shows the cumulative depth of water loss distributed for day 192 for spray, impact, and the no-irrigated condition, as well as the lysimeter measured total water use. As expected, canopy evaporation is greatest for the impact irrigated case due to the longer duration of leaf wetness. Transpiration rates were very similar and slightly greater for the spray application, again primarily due to the fact that the canopy was wetted for a longer time with the impact sprinkler. The transpiration amount is about 80% of the non-irrigated case. Soil evaporation is greater for the spray condition than for the impact, but both are similar to what was predicted for the non-irrigated case. This would indicate that sufficient soil water was available for evaporation prior to irrigation so that water was not limiting. Evaporation rates from the impact and spray irrigated areas were similar following irrigation because the method of water application has little effect on the wetness of the soil near the surface. Because the canopy and soil surface was cooled longer during the middle of the day for the impact sprinkler, the net result was a slightly lower prediction of soil evaporation for the impact sprinkler.

Droplet evaporation was 0.041 mm and 0.045 mm for the impact sprinkler and spray nozzle, respectively, representing less than 1% of the total water loss. Total measured water usage from the lysimeter was 7.6 mm for the impact irrigated lysimeter and 8.6 mm for the spray irrigated lysimeter. Although the model predicted somewhat higher water usage for both sprinkler methods than measured by the lysimeter, the spray case was within 6% of that measured.

SUMMARY

Field water balance measurements using monolithic lysimeters, micro- and mini-lysimeters, stem flow gauges, rain gauges, and meteorological parameters were used to make comparisons and validate the Cupid-DPE model for predicting water loss partioning during sprinkler irrigation with a moving lateral system. Comparisons indicate good agreement between measured and modeled rates for transpiration, soil evaporation, and total ET rates during the day of irrigation. Soil evaporation rates were under-predicted for the day following irrigation.

Droplet evaporation represented less than 1% of the total water loss for the day.

The greatest effect of sprinkler irrigation on water loss partitioning is in the reduction in transpiration and increase in canopy evaporation. This should also be reflected in the cooling of the canopy as water is evaporated from the wetted leaves. Although not studied here, data are available to make further comparisons within the irrigated canopy and the model predictions based on air temperature and vapor pressure deficit. One aspect yet to be studied is the effect on the micro-climate of wind drift into an unirrigated area or within the leading edge of the sprinkler pattern as the lateral moves into an unirrigated area. The model should provide a useful tool for making such evaluations.

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Table 1. Summary of diurnal environmental parameters for the upper boundary for day 186, Bushland, TX, 1994.

Hour of Day	Wind Speed (m s^{-1})	Solar Radiation (W m^{-2})	Dry Bulb Temp (°C)	Vapor Pres (mb)
0.25	4.1	0.0	20.2	13.47
0.75	3.5	0.0	19.6	13.56
1.25	3.4	0.0	18.7	13.83
1.75	4.2	0.0	19.1	13.65
2.25	4.3	0.0	18.9	13.47
2.75	4.1	0.0	18.5	13.29
3.25	3.9	0.0	17.9	13.47
3.75	3.7	0.0	17.8	13.47
4.25	3.6	0.0	17.8	13.29
4.75	3.3	0.0	16.5	13.29
5.25	3.4	0.0	15.9	12.86
5.75	2.7	6.3	15.7	12.27
6.25	3.1	56.6	16.1	12.35
6.75	3.4	140.5	17.3	13.47
7.25	4.3	233.8	18.9	14.02
7.75	4.5	334.5	21.0	14.87
8.25	5.6	435.0	21.6	15.07
8.75	5.2	539.3	22.8	15.57
9.25	5.9	635.3	23.9	15.87
9.75	5.5	722.1	24.7	15.67
10.25	5.6	805.2	25.5	15.67
10.75	4.8	881.2	26.3	15.07
11.25	4.1	937.3	27.1	14.39
11.75	3.9	972.5	27.7	14.58
12.25	4.5	995.0	28.4	13.74
12.75	4.6	1006.6	29.5	12.03
13.25	4.6	991.8	29.7	11.87
13.75	4.2	984.8	30.2	10.94
14.25	5.2	948.8	30.6	10.94
14.75	5.4	890.9	30.8	11.40
15.25	4.9	843.5	31.0	10.36
15.75	5.6	777.6	31.2	9.61
16.25	5.5	676.6	31.3	10.15
16.75	5.7	579.2	31.2	10.22
17.25	5.8	476.5	31.1	9.61
17.75	5.3	381.1	31.0	9.88
18.25	5.7	267.3	30.7	10.01
18.75	5.4	161.1	30.2	10.58
19.25	5.7	81.3	29.5	10.65
19.75	4.0	18.0	27.9	10.58
20.25	4.9	0.0	26.3	11.47
20.75	4.4	0.0	24.9	11.24
21.25	3.7	0.0	23.4	10.94
21.75	3.5	0.0	22.3	10.72
22.25	3.1	0.0	21.3	10.65
22.75	3.1	0.0	20.5	10.58
23.25	3.8	0.0	20.3	10.72
23.75	4.7	0.0	21.1	11.32

Table 2. Summary of diurnal environmental parameters for the upper boundary for day 192, Bushland, TX, 1994.

Hour of Day	Wind Speed (m s^{-1})	Solar Radiation (W m^{-2})	Dry Bulb Temp (°C)	Vapor Pres (mb)
0.25	5.7	0.0	21.5	14.20
0.75	5.8	0.0	20.8	14.11
1.25	6.8	0.0	21.0	14.20
1.75	7.3	0.0	21.0	14.39
2.25	7.6	0.0	20.7	14.77
2.75	8.3	0.0	20.6	14.97
3.25	6.9	0.0	20.1	15.07
3.75	5.9	0.0	19.6	15.07
4.25	5.9	0.0	19.8	14.97
4.75	5.7	0.0	19.7	14.97
5.25	5.2	0.0	19.3	14.97
5.75	4.3	5.0	18.9	15.07
6.25	5.3	41.2	19.2	15.27
6.75	5.6	41.0	18.9	15.47
7.25	5.5	138.8	20.0	16.08
7.75	6.8	244.0	21.6	16.50
8.25	8.7	427.5	23.3	16.83
8.75	9.4	526.4	24.3	17.04
9.25	8.5	610.4	25.3	17.49
9.75	8.3	707.3	26.5	17.83
10.25	7.6	785.7	27.6	17.71
10.75	7.5	854.4	28.5	17.38
11.25	7.0	911.8	28.9	17.26
11.75	6.6	951.5	29.6	17.15
12.25	7.1	976.8	30.3	17.04
12.75	6.8	922.5	30.7	16.40
13.25	7.5	792.0	31.0	15.57
13.75	7.5	717.2	31.1	15.47
14.25	7.8	606.4	31.0	15.98
14.75	6.8	579.6	30.8	14.97
15.25	7.1	521.1	31.0	15.87
15.75	8.5	767.9	31.6	15.57
16.25	7.6	649.5	31.5	15.87
16.75	8.2	472.3	31.7	15.87
17.25	8.4	466.5	31.8	15.57
17.75	8.2	382.7	31.9	15.36
18.25	8.0	277.8	31.6	15.47
18.75	8.1	148.3	31.1	14.77
19.25	6.8	76.4	30.6	14.30
19.75	5.1	11.9	29.3	14.02
20.25	3.8	0.0	27.5	13.65
20.75	3.2	0.0	26.5	13.47
21.25	4.1	0.0	25.7	13.38
21.75	4.5	0.0	25.3	13.92
22.25	4.3	0.0	24.7	14.11
22.75	4.1	0.0	24.1	14.11
23.25	4.2	0.0	24.1	13.83
23.75	4.0	0.0	23.5	13.92

Table 3. Summary of field conditions for days 186 and 192, Bushland, TX 1994.

Day	Twater (°C)	Lysimeter* NE	Lysimeter* SE	Plant height (m)	LAI
186	17.8	---	Spray (22)#	0.95	2.1
192	22.1	Spray (27)	Impact (23)	1.40	2.4

* NE is the Northeast lysimeter
SE is the Southeast lysimeter
\# numbers in parentheses are application depth in mm.

Table 4. Summary of water loss partitioning for day 192, Bushland, TX, 1994.

	Canopy Evap (mm)	Transp (mm)	Soil Evap (mm)	Droplet Evap. (mm)	Predicted Total Water loss (mm)	Lysimeter total measured (mm)
Impact	2.68	4.62	2.41	0.04	9.67	7.6
Spray	1.45	4.80	2.85	0.05	9.14	8.6
Dry	---	5.96	2.53	---	8.51	---

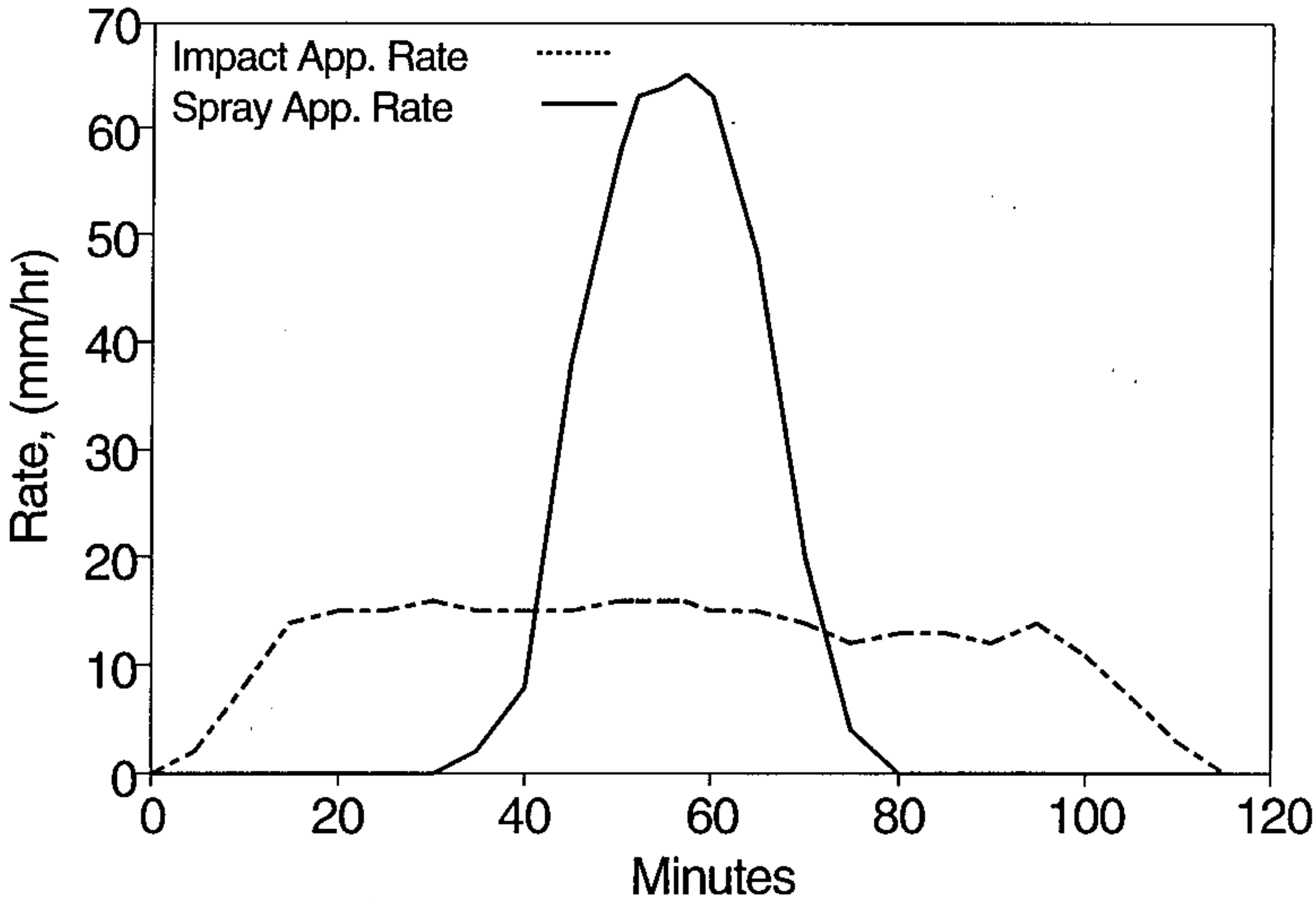

Figure 1: Application Rate Patterns for Impact Sprinker and Spray Nozzle.

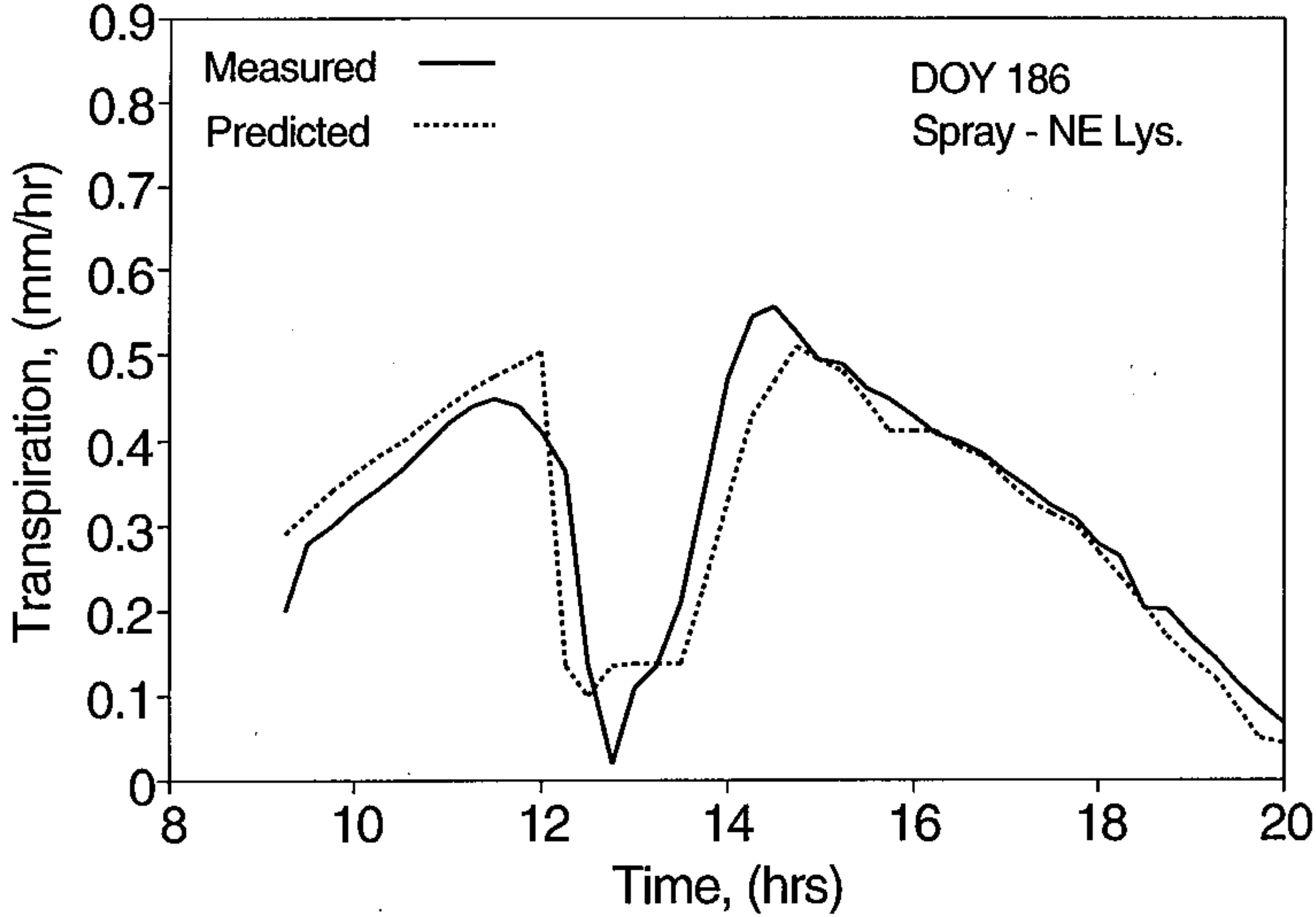

Figure 2: Comparison of Measured and Predicted Transpiration Rates for Day 186, Spray Irrigation.

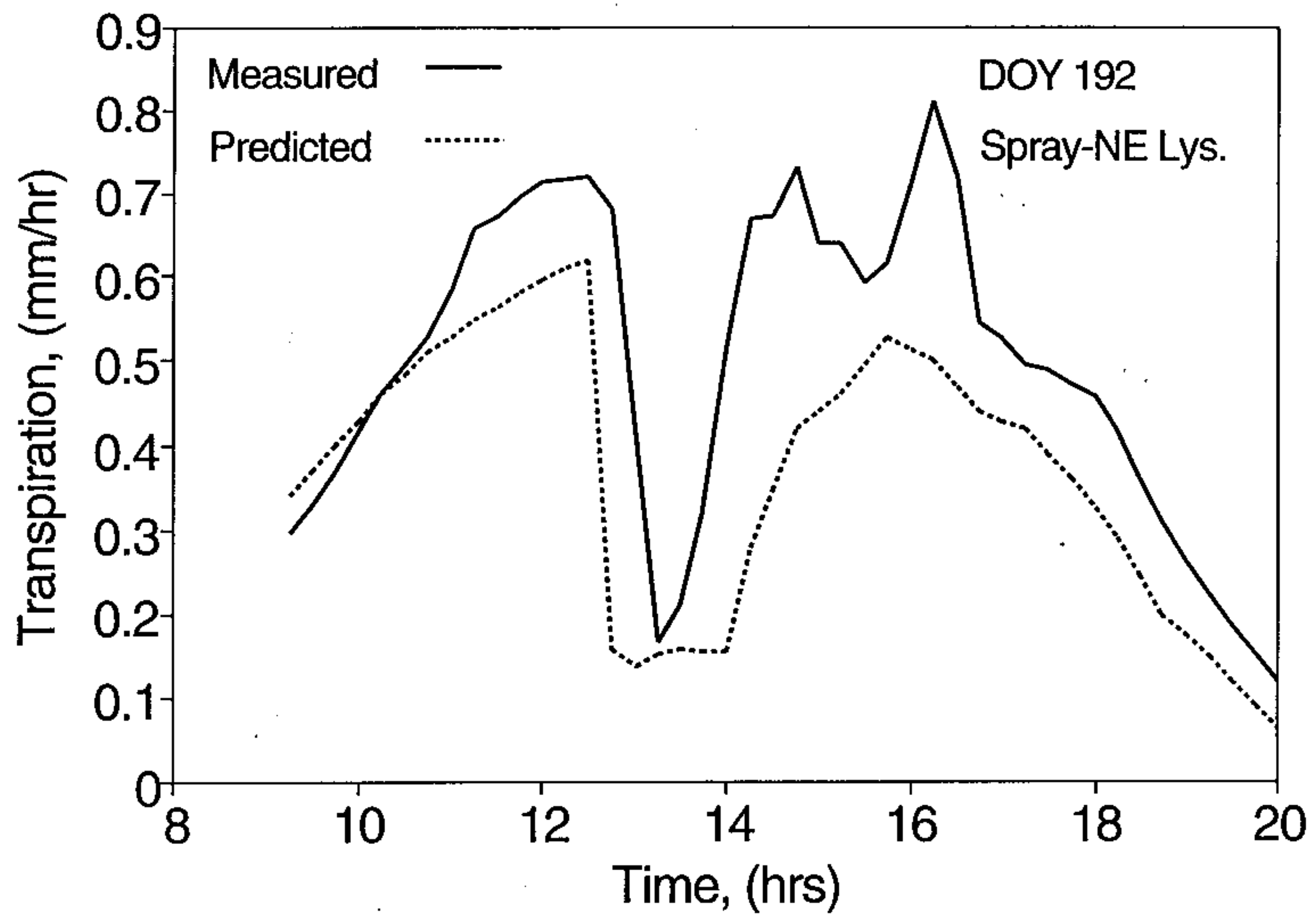

Figure 3: Comparison of Measured and Predicted Transpiration Rates for Day 192, Spray Irrigation.

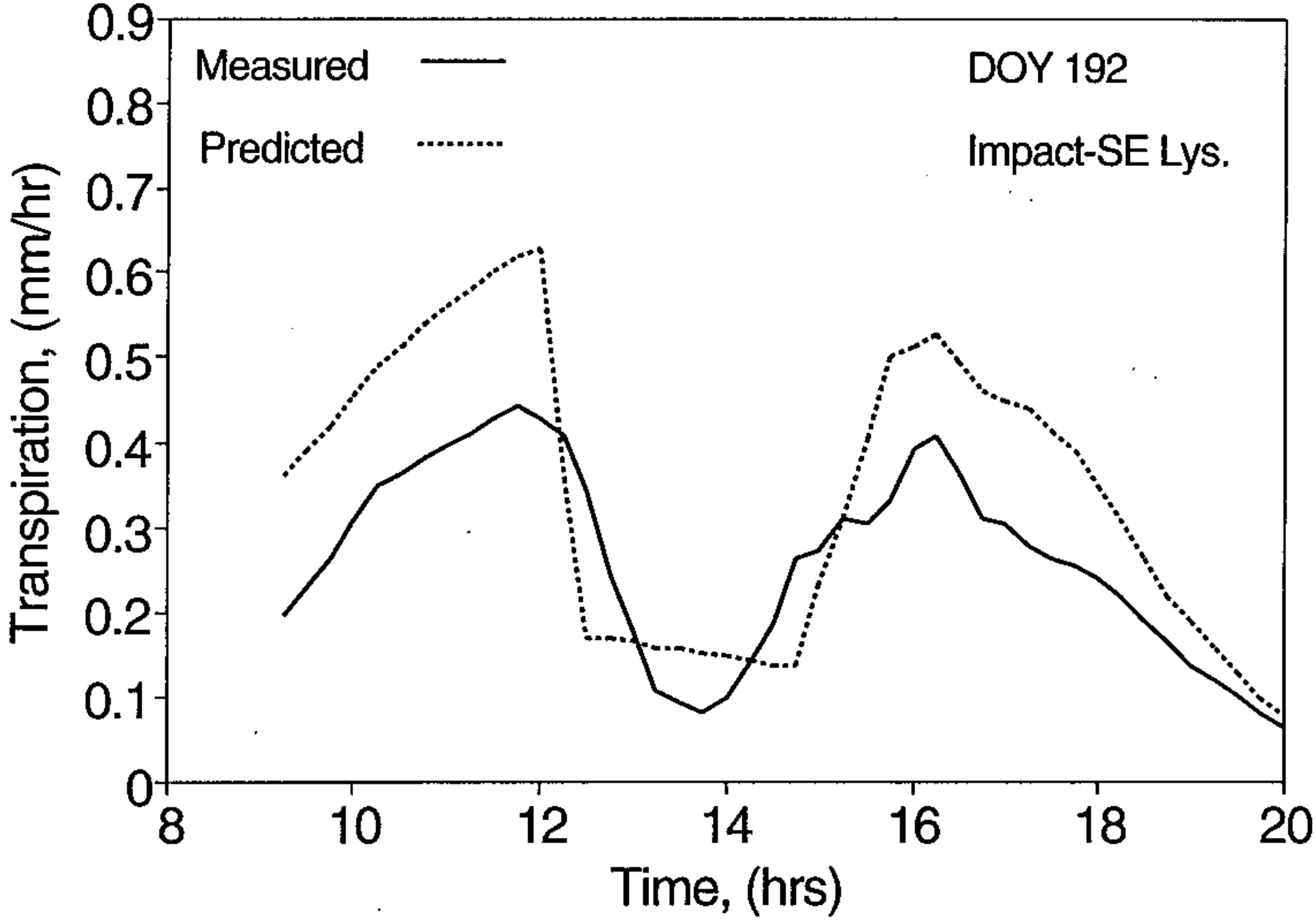

Figure 4: Comparison of Measured and Predicted Transpiration Rates for Day 192, Impact Irrigation.

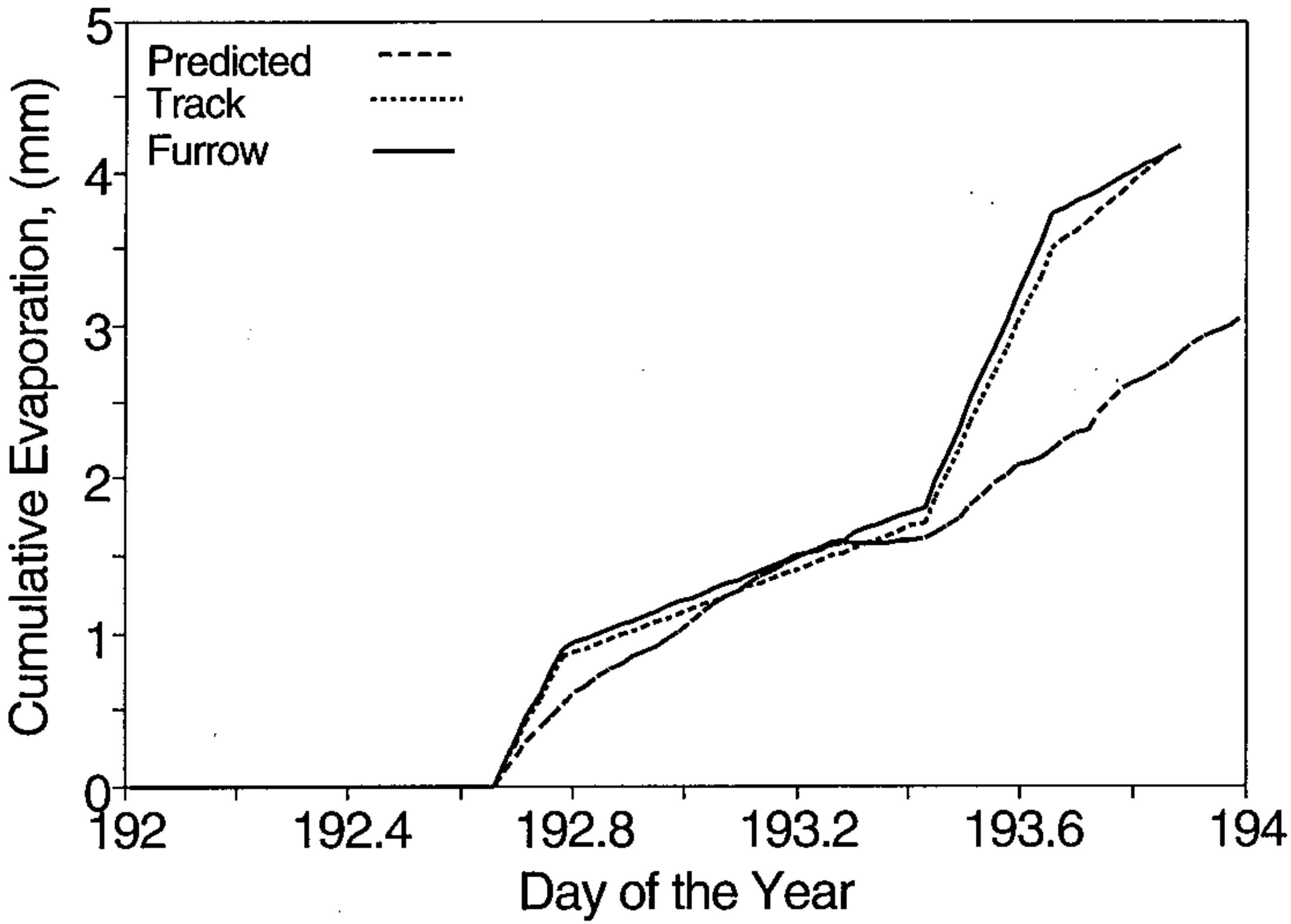

Figure 5: Comparison of Predicted and Measured Soil Evaporation Rates for Days 192 and 193.

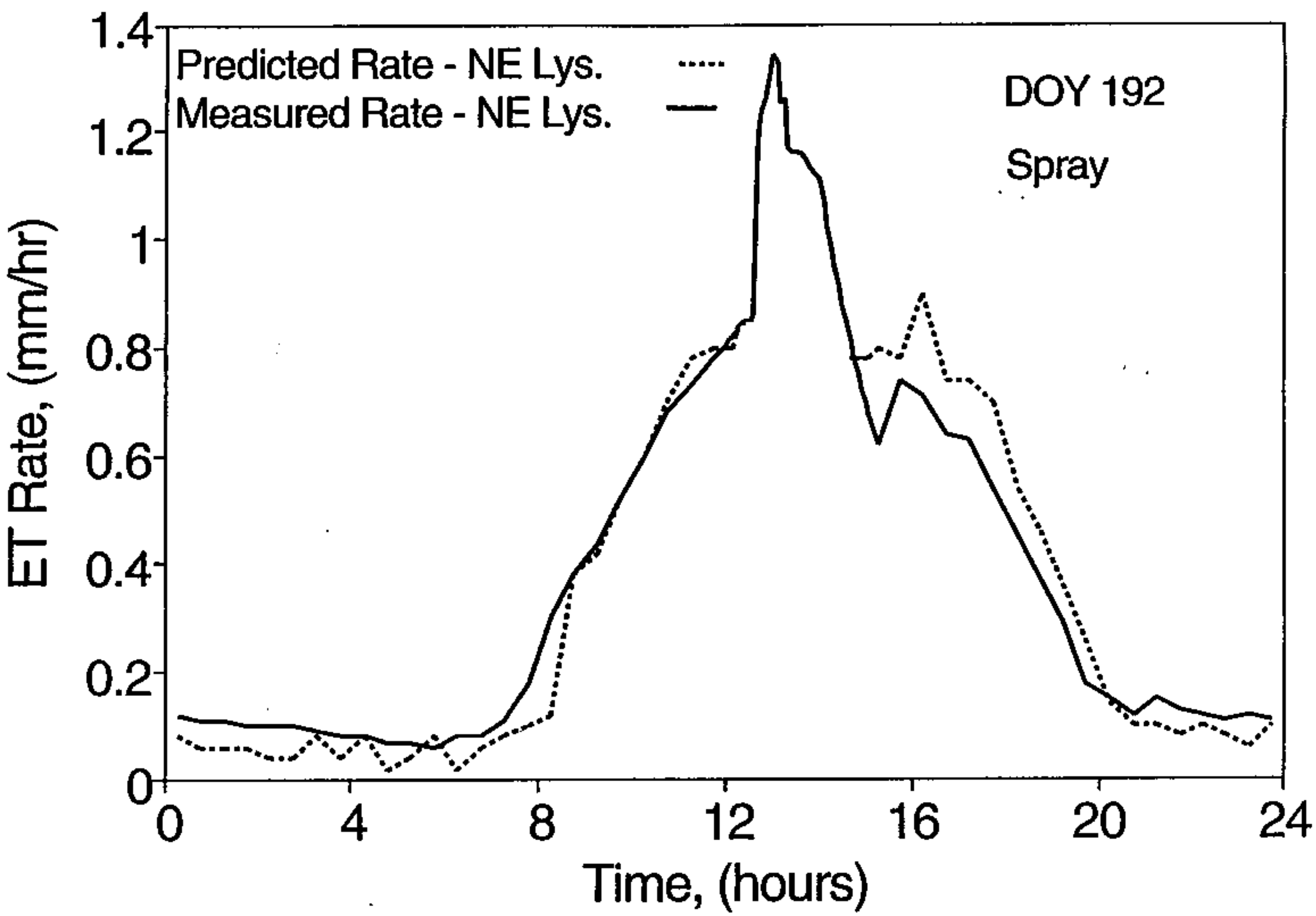

Figure 6: Comparison of Measured and Predicted Evapotranspiration Rates for Day 192, Spray Irrigation.

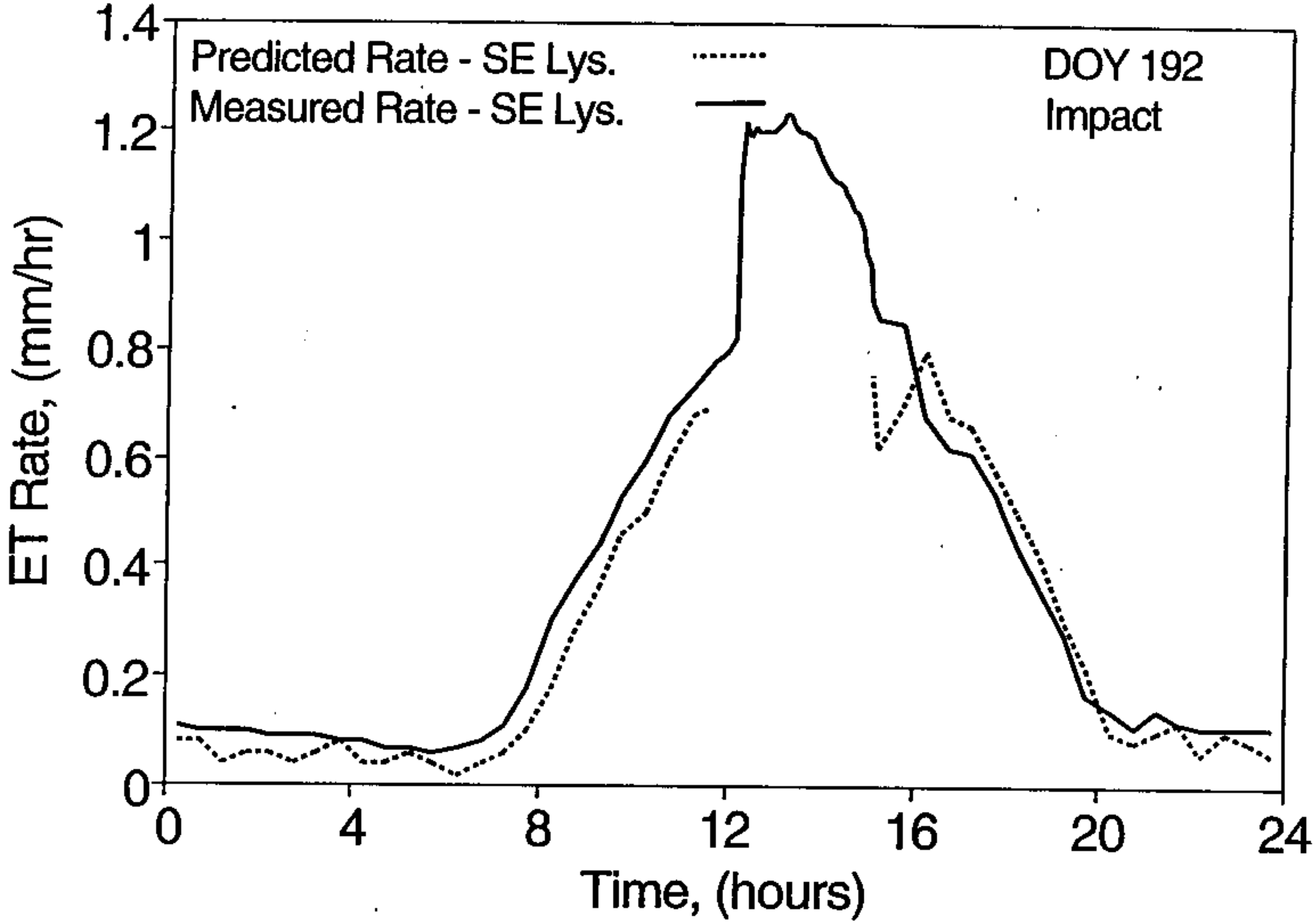

Figure 7: Comparison of Measured and Predicted Evapotranspiration Rates for Day 192, Impact Irrigation.

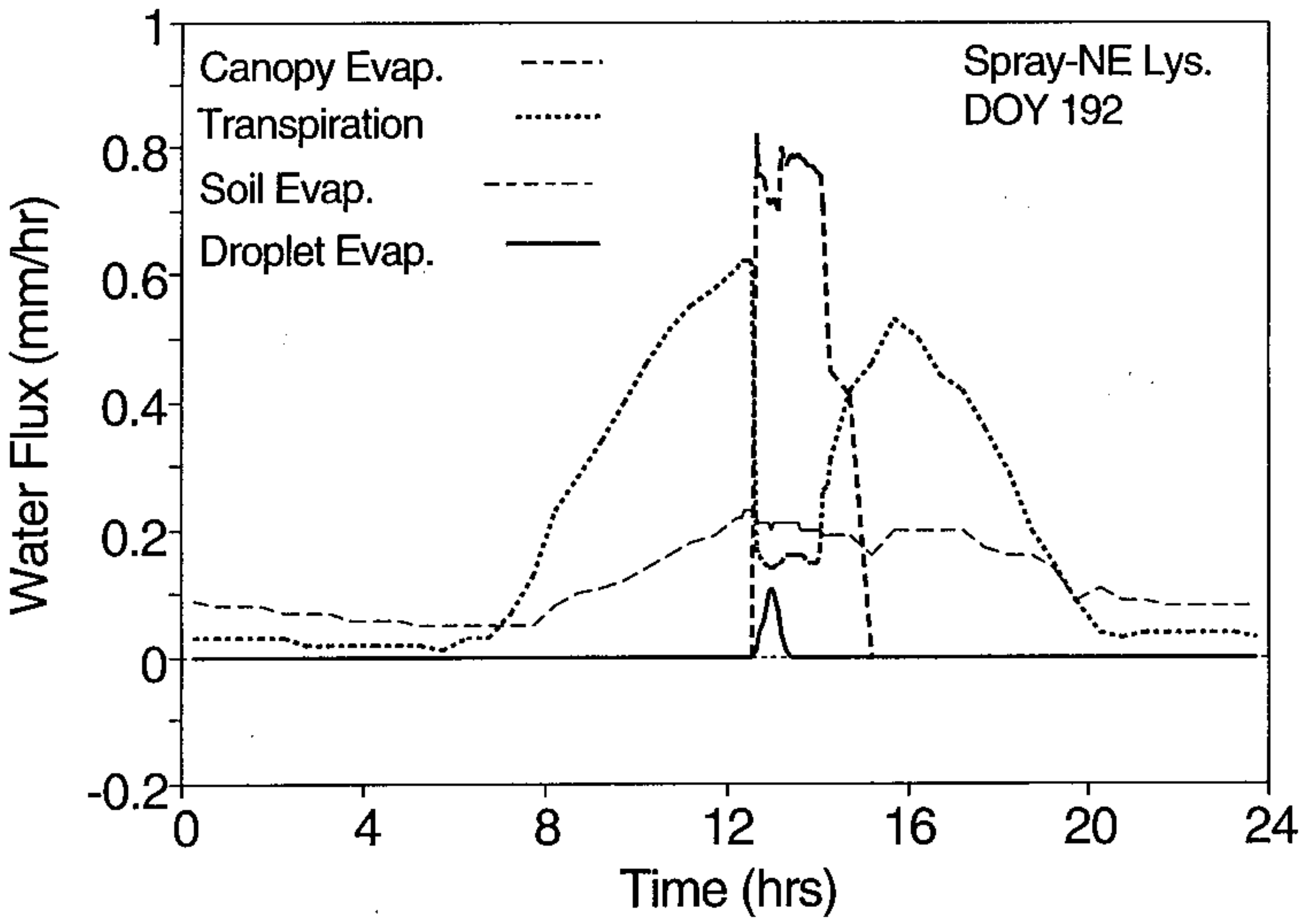

Figure 8: Predicted Diurnal Water Budget for Day 192, Spray Irrigation. Irrigation was from 12:35 to 13:20.

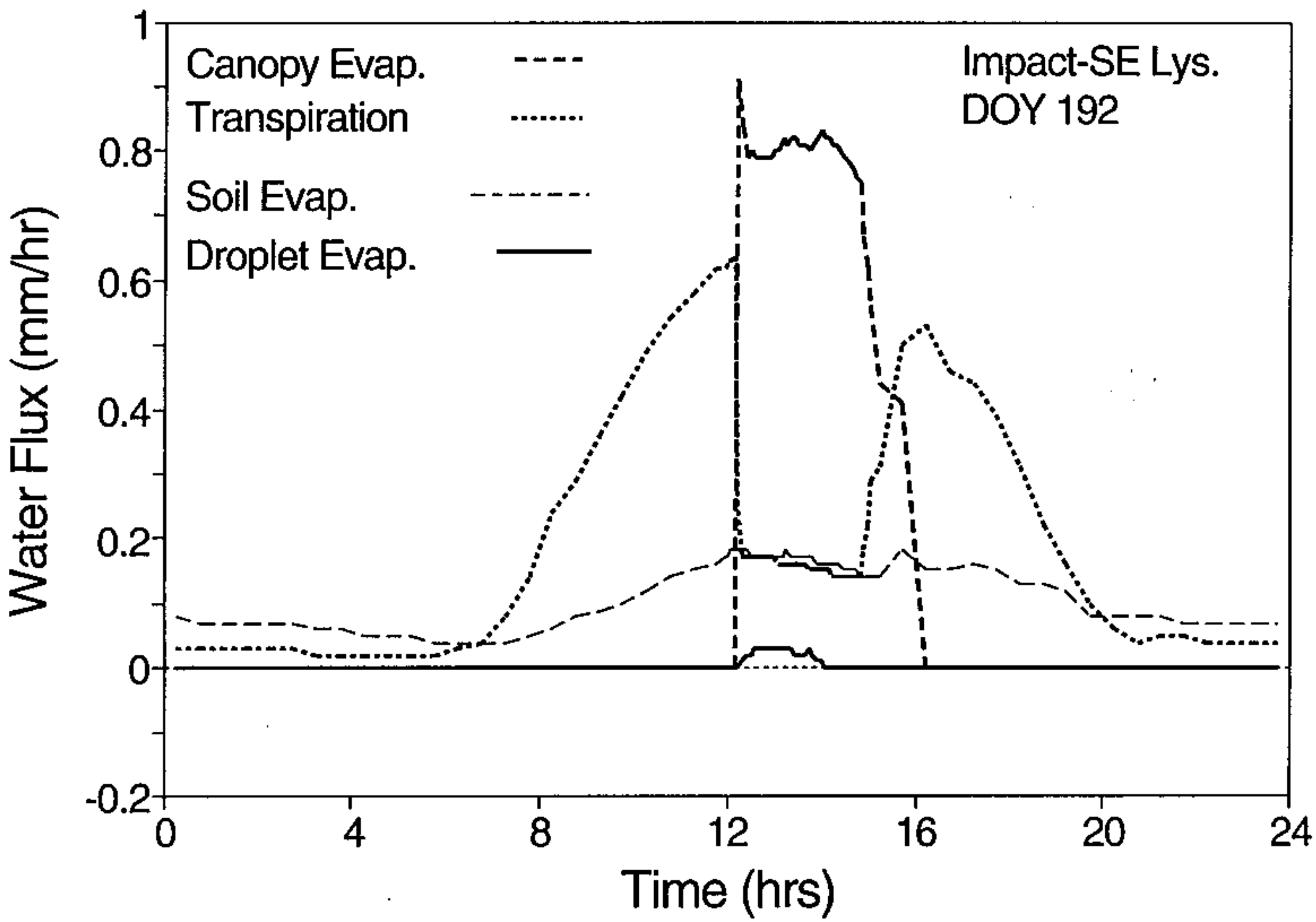

Figure 9: Predicted Diurnal Water Budget for Day 192, Impact Irrigation. Irrigation was from 12:10 to 14:05.

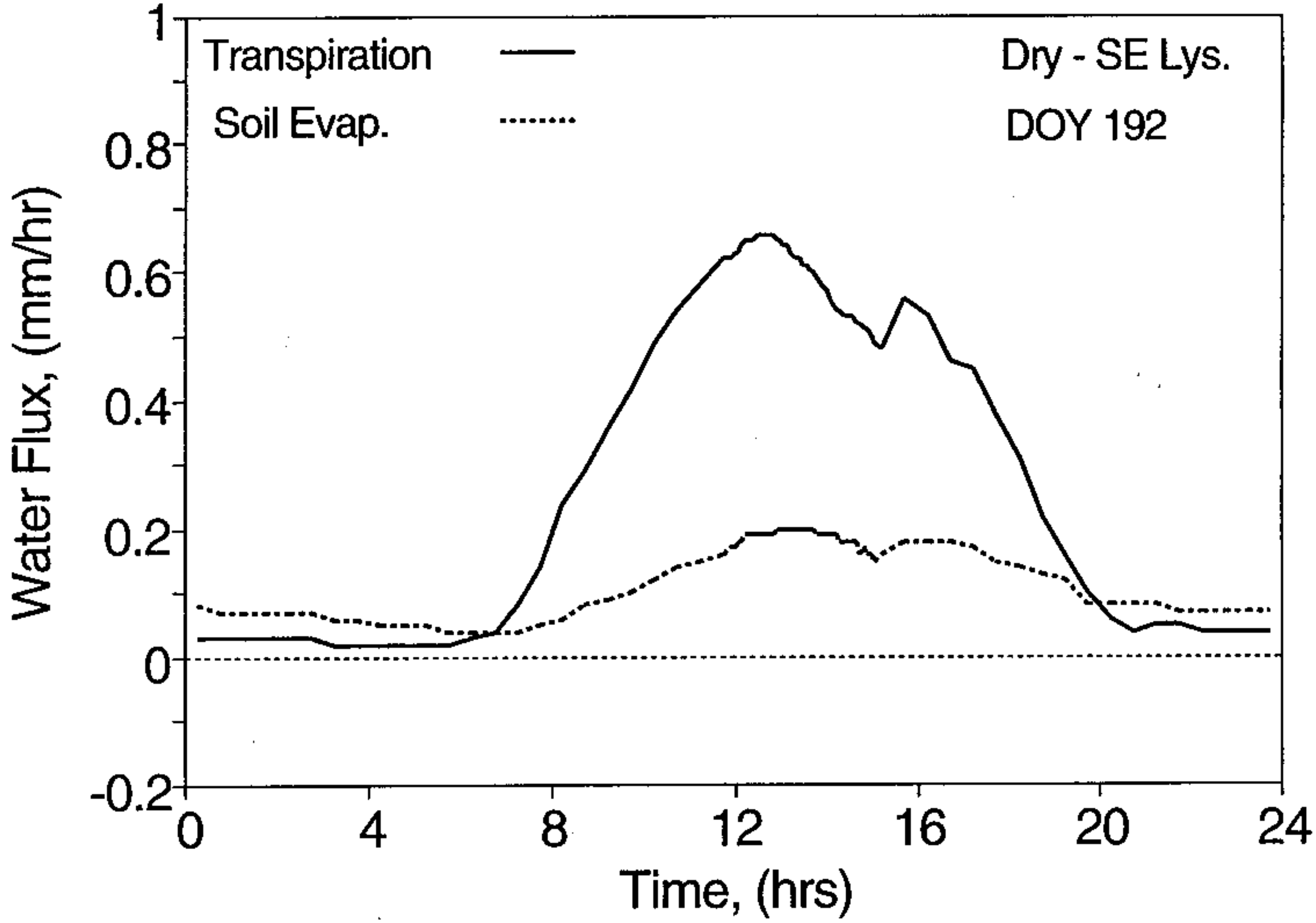

Figure 10: Predicted Diurnal Water Budget for Day 192, assuming no irrigation.

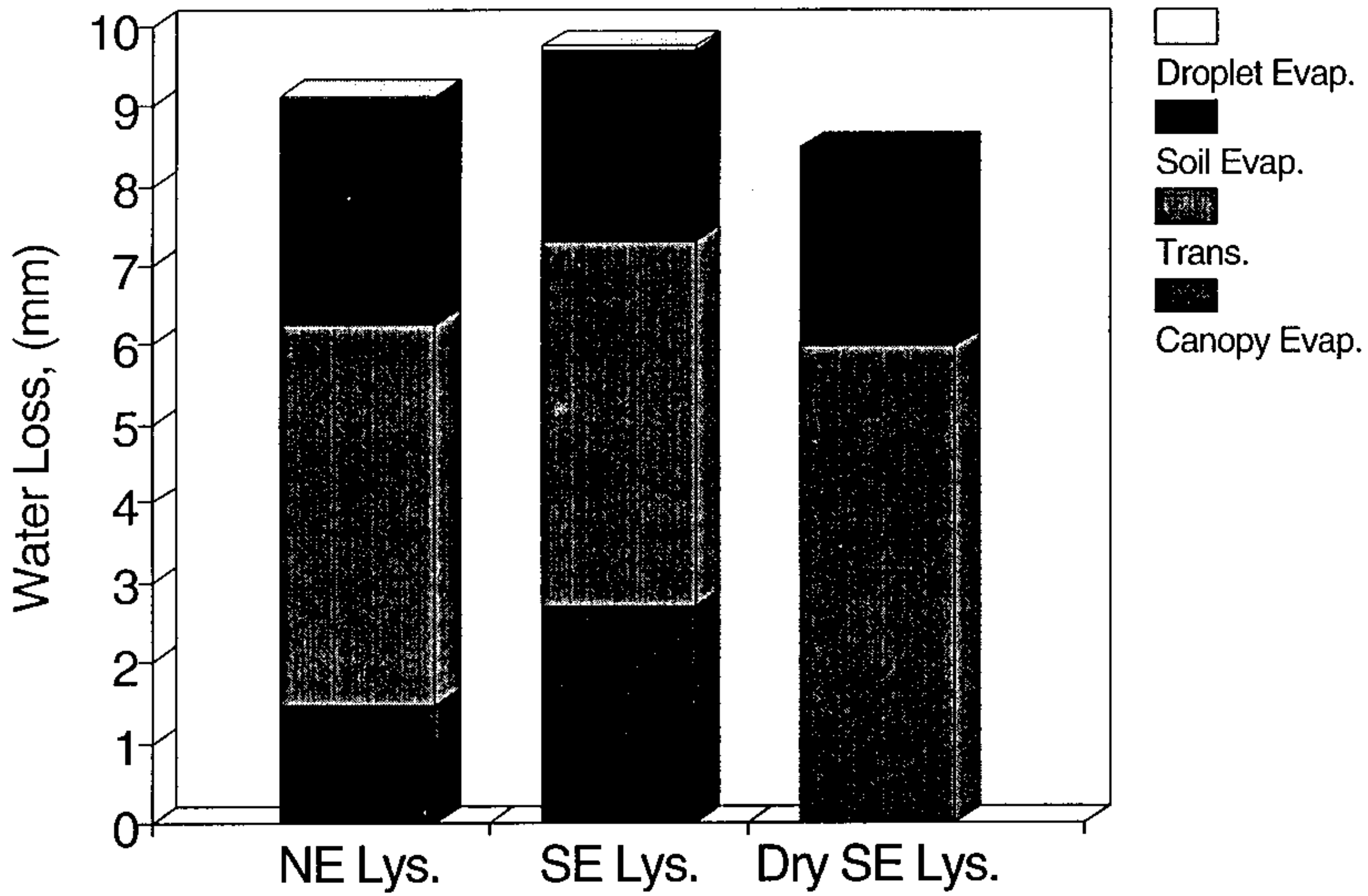

Figure 11: Cumulative Water Budget for Day 192 for Spray, Impact and no irrigation.